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Solar optimization of housing development

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Abstract

This study explored how to increase the on-site energy production of row-houses in a new urban development area located in Trondheim (Norway) from the early design stages. The process consisted in an evolutionary algorithmic for optimizing the shape of the building's roof in order to maximize the use of solar energy. Starting from the roof's profile of the traditional Norwegian house unit, different configurations have been tested. The process allowed changing iteratively the inclination and the size of the roof's surfaces. The selected roofs' shapes guaranteed to get the maximum solar radiation and the solar mapping analysis allows individualizing the most suitable areas to install solar systems on the roofs' surfaces of the entire district. The final configuration of the row-houses permitted to increase the solar potential around 30% respect the initial design solution.

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Keywords: solar optimization; building integrated energy production; renewable energy production.

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1. Introduction

According to the International Energy Agency (IEA), the residential buildings are responsible for more than 25% of the total energy consumption [1]. A decrease to their energy footprint could positively affect their environmental, economic and social contribution towards to a more sustainable way of planning and living. In this scenario, the use of the renewable energies plays a relevant role and their integration in the design at building and district scale is becoming a priority in the urban planning [2]. However, despite solar radiation being sufficient especially in southern and central of Norway (annual horizontal insolation around 900 kWh/m^2 in Grimstad [3]), the electricity production from solar energy still remains not significant [4]. Although solar radiation has a great potentiality to be converted into energy for building, the difficulties are mostly related to the unpredictability and unreliability [5] [6] . Therefore, new approaches for better integration of solar systems into the building envelope and preliminary evaluation of energy use should increasingly be taken into consideration during the early design phases of urban planning processes. Several studies showed the potentialities in conducting analyses at different design stages. The

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combination of passive and active strategies early in the design process is a challenge but at the same time it represents an opportunity to guide designers towards the objectives of the energy optimization and environmental impact.

In the Subtask B "*Tools and methods for solar design*" within the Task 41 "*Solar Energy and Architecture*" initiated by the International Energy Agency (IEA) the Solar Heating and Cooling (SHC) Programme, were identified the barriers that architects have to face in the implementation of solar active and passive strategies. Traditionally the challenge is purely represented by an economic issue of the time consuming in learning and using the tools. In fact, they require a high level of expertise, and software packages that are not always freeware [7]. Another barrier is the general lack of awareness and knowledge of the different technologies amongst building professionals which are usually uncertain in using correctly the software [8] [9]. Furthermore another critical aspect is to overcome some theoretical and technical barriers due to the difficult interaction between architect, engineers, manufacturers and clients. The use of the software in the early design phase could have a twofold effect: on the one hand improve their dialogue and, on the other hands guide them towards the right design and technical decisions. In fact at these stages, the most important and influenced decisions were taken. They could determine the success or failure of the entire design process. Regarding the solar architecture, the combined integration between design tools and solar analyses' software allows to assist urban planners and architects to address the most influenced design decisions towards solar accessibility and solar potential optimization. Therefore, they have to focus their analyses on the shape of the buildings, their orientation, the design of the façades, the choice of the finishing materials, the glazing parts etc. which are usually defined during the early design stages of the process [8] [10] [11]. In that respect, the survey and the interviews conducted in the Subtask B of Task 41 indicated the need of developing design tools for solar architecture with a more user-friendly interface in order to facilitate the visualization and interpretation of the software outcomes as well as the interoperability within the environments of the existing modelling tools [12]. The discussion of this topic was extended at urban scale and it is actually under investigation within the SHC - IEA Task 51 "*Solar Energy in Urban Planning*". In this framework, and in particular within the Subtask C "*Case studies and action research*" of SHC – IEA Task 51, this work represents a case study where it was developed a solar optimized design district combining modeling tools with solar dynamic simulation software from the early design phases.

2. Aim

The continuous development of the city of Trondheim due to the increase of population has generated a further need for residential buildings. The Norwegian Statistics Centre (SSB) has estimated that from 2000 to 2030, there would be an increase of 70,000 inhabitants. It is expected that this figure will be surpassed due to the fact during the period 2000-2011 the city has shown an even faster growth than the estimated by the SSB center [13].

In this framework, the aim of this paper is to design a Net-Zero Energy Housing Development achieving a yearly-based energy balance between the energy demand for the operation of the buildings and the on-site renewable energy production [14]. The potential of implementing renewable energy production from the early design phases of the building's design process has been explored. In that sense, a solar optimization process was developed in order to increase as much as possible the solar radiation that can be harvested on the building's roof. By starting from a typical Norwegian vernacular architecture house unit, better known as "gable roof" [15], the surfaces of the roofs was modified by combing parametric tools (i.e. *Rhinoceros* and *Grasshopper*) and solar dynamic simulation software (i.e. *DIVA for Rhino*) in order to calculate the most suitable profiles of the building able to maximize the solar radiation potential.

2.1. Norwegian background on Solar Energy

The use of solar energy in Norway is strongly discouraged due to the adverse weather conditions and to the appearance of low solar potential in high latitudes. From this assumption several myths raised up in Scandinavian environment during the last decades: (i) the temperatures are too low for guaranteeing the efficiency of the system, (ii) the solar angle is low at high latitudes, (iii) the presence of darkness in the winter decrease the solar potentiality. They contributed in decreasing the installation of solar systems in Norway.

However, a study conducted by Nordic Energy Research [16] revealed that the solar radiation received by a track-sun system installed in Sweden is equivalent to an identical system localized in Germany. Despite the number of solar systems' installation in Norway remains very low and the solar technology is still not popular in both fabrics, private and public, the solar energy is becoming more and more used [17] [18]. This improvement is also given by the increase standards on energy regulations and by the Norwegian commitment towards reducing 30% CO_2 emissions in buildings by the year 2020. The presence of small systems (below 1 kW) installed on vacation houses as well as larger-scale solar energy projects were realized in Norway in the last couple of years [19]. Among them, the most important are the large PV systems of Oseana Culture Center, Campus Evenstad, and the intervention of renovation of Powerhouse Kjørbo as well as the solar thermal of 13 000 m^2 installed by Akershus energy. Despite the energy demand of Norwegian residential buildings is mostly composed by heating and the use of active systems could represent an important alternative, the solar installations still strongly depended from private initiatives. Furthermore, the lack of a dedicated legislation that regulates the use of solar energy in Norway doesn't help the development of the technology in the country. In that sense, for new buildings in existing urban areas or for new entire urban developments is becoming necessary to conduct analyses from the early design phases in order to guarantee solar access and to prevent the reduction of solar availability of buildings due to the overshadowing effect created by the nearby urban areas [20]. In that context is emblematic the case study of a commercial building in Trondheim: it showed that missed preliminary analysis could cause a significant issue of solar accessibility in urban environment by reducing up to 50% the solar potentiality of the photovoltaic system installed on the South façade of the commercial building [21].

In Norway a dedicated action plan that regulates the right of light, energy requirements, viability, energy supply etc. for each new urban zone, has to be developed before starting the buildings' construction. In this scenario, this study represents the first attempt to design a new district with solar integrated systems modelled by solar energy and regulated by the principle of right of light in order to reach both objectives: maximize the solar radiation's exploitation of the building envelope and guarantee the solar accessibility of the designed buildings.

2.2. Study area

The study was based on the new urban development area of Øvre Rotvoll (dashed yellow lines in Fig. 1), located in East part of the city of Trondheim (latitude 63°25'N, longitude 10°23'E) between the center and the residential neighborhoods of Charlottenlund and Ranheim. The area of Øvre Rotvoll has the ambitious to become a new strategic development area designed according to the energy targets of the net-zero energy neighborhood as well as able to connect different parts of the city. In particular, in this paper the study was limited on a small part of the whole area interested by this intervention (area in red hatch in Fig. 1).

Fig. 1. (On the left) Localization of the new development area of Øvre Rotvoll: in yellow dashed line the entire area, in red hatch the site project of this work (Source: google maps); (on the right) the enlargement of the site plan of the studied housing development area.

The buildings are placed on the site according to the layout development, developed during the urban planning phase. The disposition of the buildings' blocks was studied in order to create on the one hand, an open courtyard that works as a public social square and, on the other hand, a physical connection with the existing forest on the East. The distance among the buildings blocks was set in order to guarantee solar accessibility to more than 30% of the South, East and West façade, during the period between the 21st of March and the 21st of September. This setting allowed optimizing passive and active strategies as much as possible during the maximum daylight period at Trondheim latitude. On the site plan, three kinds of house orientation have been set: the South/North, the East/West and rotated 30 degrees to West from the axis of South-North.

3. Methodology

The volume of an *initial* resident unit (a) was defined conducting a literature review on the needs of a typical family in Norway living in traditional dwellings. The initial residential unit consists of two storeys of three meters high each, and on a footprint of 80m^2. The facade's width was fixed equal to eight meters while its depth was set by ten meters. For the roof, it was chosen an inclination ratio of 40% that can be considered as a typical roof slope according to literature review on roof typologies for Norwegian houses [15]. Based on this unit, the area and the volume of a typical Norwegian house unit have been defined (Fig. 2).

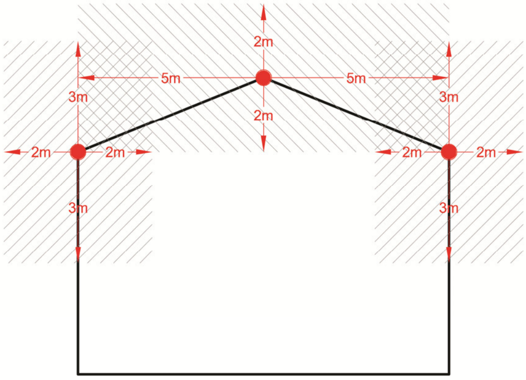


Fig. 2. The initial unit section: the red dots represent the movable vertexes; the arrows show the direction of movement while the grey hatch indicates the available domain of movement.

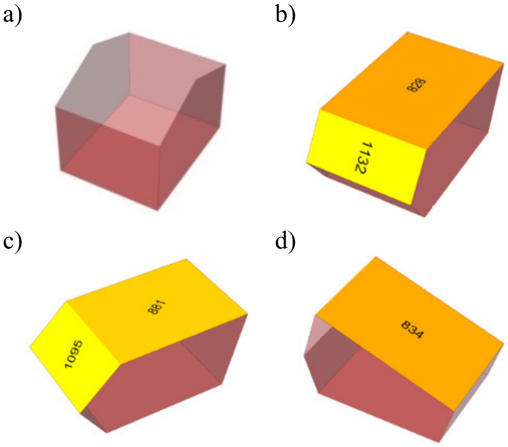


Fig. 3. The units of the optimization process: a) initial unit, b) Optimized 01 North-South, c) Optimized 02 - 30° South-West, d) Optimized 03 - East-West.

Starting from this unit, a parametric design was applied in order to test a wide range of design cases in order to optimize the solar radiation harvesting by the roof's surface. In this process, the relations among different variables defined the shapes carried out. In this case study, the optimization process of the shape of the *initial* unit has been made by using a digital parametric language in *Grasshopper for Rhinoceros* environment. *Rhinoceros* as a visual programming tool for *Grasshopper* that allows parametrical control and generation of complex 3D models. The *Galapagos* plug-in within *Grasshopper* was used to test automatically several scenarios through an evolutionary algorithm. A randomly created group of multi-objectives solutions were compared according to a fixed fitness such as the compactness index defined by the ratio of surface and volume (S/V). The process allows extracting the best solutions, which higher (or lower) value. Galapagos optimizes iteratively the next generation of multi-objectives solutions by using the best one carried out from the previous generation process and by applying some additional computing techniques for better control the entire evolution process.

In order to perform the solar optimization process on the roofs' inclination, dynamic solar radiation simulations were conducted using *DIVA for Rhino*, a Radiance-based tool for Rhino-Grasshopper platform.

This process, started from the transformation of the size and the slope of the building envelope. This operation was done for all the three existing orientations (South/North, East/West and 30° South/North). Only the edges of the roofs were able to change position: they were set as the primary variables with a freedom of movement along both, horizontal and vertical axis. Roof base edges were able to move in a given domain of two meters horizontal distance from the initial point and three meters in vertical direction. The edge of the top of the roof was able to move up to five meters towards each side horizontally and two meters vertically (Fig. 3).

The three parameters that affect energy performance have been taken into consideration and examined:

- The **irradiation** that arrives on the surfaces of the building envelope. It measures the solar potentiality of the building. Its estimation allows calculating how to integrate photovoltaic panels on building's roof and façades. The inclination and the size of each surface affect drastically this parameter. The irradiation on each surface was calculated by using *DIVA for Rhino*.
- The **compactness index** of the building that is given by the ratio of the building's envelope in relation to its volume (S/V). Higher compactness corresponds to lower thermal losses through the walls, floor and roof, helping to achieve better energy performance. The energy envelope standards were taken from the NS3700 and NS3701 [22].
- The **volume** of the indoor space that is related to the amount of energy used for heating and cooling.

In the process, for each given position of the edges that was tested, the compactness and the volume of the new shape has been calculated. Afterwards, the received irradiation per square meter on the defined surfaces of each shape was simulated and then the total irradiation was calculated. The process has iteratively continued by changing the position of the edges of the roof until reaching the optimized configuration that optimized the solar radiation on the roof.

In the next step, this fitness (S/V) was fixed by using *Galapagos*. It allowed to compare the ratio (irradiation/compactness) among 50 created volumes in the given domain. Through the process were obtained between 80-120 loops for each of the three orientations. Each time, the new positions of the edges were changed upon the positions of the previous configuration that had given the highest ratio of irradiation to compactness.

Through this process, the *initial* house section was modified in order to obtain the optimized section for each of the three orientations (Fig. 3). The results of irradiation had been cross checked by comparing the received irradiation values for the same orientation on the web application of *PVGIS* [23].

4. Results

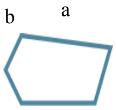
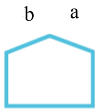
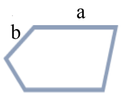
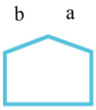
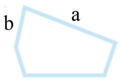
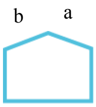
The analyses demonstrated that the *optimized* units receive approximately more than 50% more irradiation than the *initial* unit for South/North and 30° South-West orientations and more than 35% in the East-West orientation. The *optimized* units give the highest amount of irradiation on the selected surfaces: roof a and roof b (Table 1 and Fig. 4).

According to the orientation of each block, the final configuration of the buildings in the neighborhood was composed by combining the initial profile positioned at the beginning and at the end of the blocks and the optimized profile at the middle of the length of the block. The respective optimized profile was positioned where the direction of the block is changing (Fig. 5). The expected solar radiation received by roof surfaces is approximately 3.855.000 kWh per year.

In order to estimate the potential energy production by the available amount of irradiation, it was decided to be examined high efficiency PV panels in accordance to the architectural idea. The solar cells that were selected have 22% efficiency. In order to calculate the percentage of useful PV cell area, a sample of four different sizes of panels was selected. From the resulting comparison of Panel Area and Cell Area in the samples, an average around 80% was determined to be applied in the energy production calculation.

The energy production on the buildings was calculated considering the cell's efficiency, available cell's area and solar radiation per m^2. The total energy production resulted equal to 140.8 kWh/m^2/year.

Table 1. Comparison of the properties and values for optimized and initial volumes (shown as vertical sections) for each orientation.

Concept	South-North		30° South-West		East-West	
	Optimized	Initial	Optimized 02	Initial	Optimized	Initial
Shape						
Compactness (S/V)	0,75	0,72	0,75	0,72	0,78	0,72
Volume (m^3)	554	560	558	560	495	560
Surface roof a (m^2)	95	43	84	43	91	43
Surface roof b (m^2)	30	43	35	43	35	43
Irradiation per sq.m on roof a (kWh/m^{2}yr)	828	640	884	675	843	866
Irradiation per sq.m on roof b (kWh/m^{2}yr)	1132	1059	1095	1047	703	849
% of increment of solar potential (Optimized vs Initial unit)	**+ 54%**		**+ 52%**		**+ 37%**	
Total irradiation (a+b)/Compactness [kWh/m^2]	**150160**	**101468**	**150108**	**102842**	**129895**	**102424**

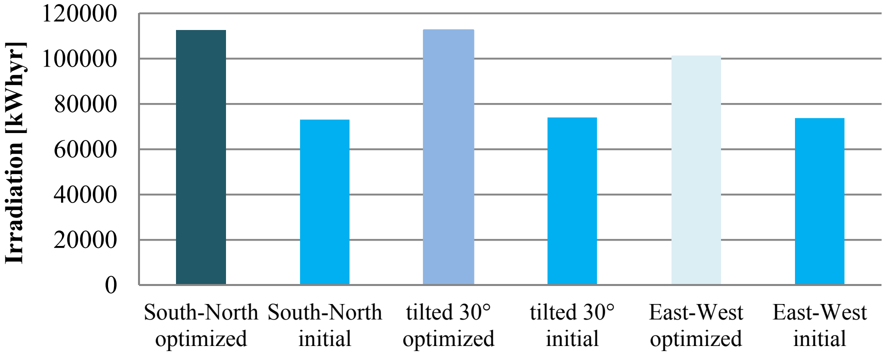


Fig. 4. Received irradiation per year on both roof sides in kWh per year

Therefore, the annual energy production, by using an appropriate PV technology, could reach 146 kWh/m^2 while the operational energy consumption could reach 75kWh/m^2 for the whole building complex. This amount of energy allowed covering approximately twice the operational energy demand of the entire neighborhood.

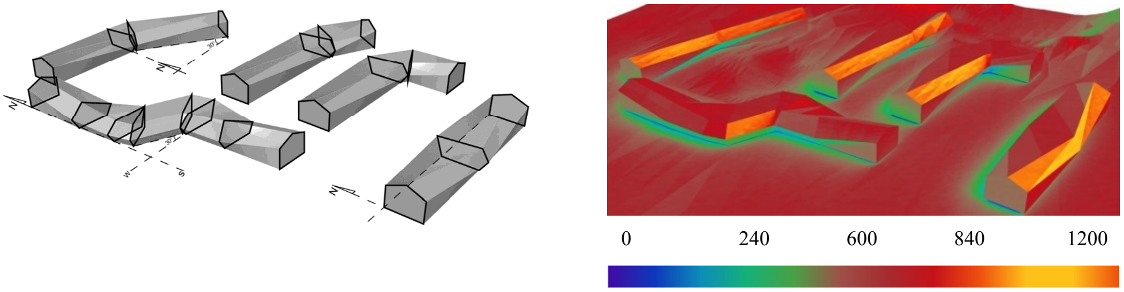


Fig. 5. Representation of the buildings composition (on the left); Solar radiation maps of the optimized scenario (on the right).

The housing development project was also analyzed regarding the energy and CO_2 emissions balance. In order to determine the ZEB level of the project, a comparison between the CO_2 emissions from the energy consumption and materials with the energy produced, has been realized. For the conversion of energy consumption and production from kWh to $kgCO_2eq$, the ZEB factor for energy in Norway of 0.132 $kgCO_2eq$ has been used. As a result, the total CO_2 emissions from the materials and operation rendered 19.20 $kgCO_2eq/m^2$BRA/year and for the energy production was 19.35 $kgCO_2eq/m^2$BRA/year. Therefore the level of zero emission building has been reached.

Fig. 6. Rendering of the project.

5. Discussion and conclusion

The main purpose of the work was to define how energy efficiency behavioral strategies and on-site renewable energy production can be implemented in the design of a housing development, as well as to which extent can these strategies impact the energy and CO_2 balance. The site is developed based on the concept of eco-city as a sustainable urban form, thus emphasizing in the reduction of the ecological footprint (Fig. 6).

The produced energy by integrated photovoltaic panels on the optimized building envelope is enough not only to cover the operation needs, but also to compensate the biggest part of the embodied energy in materials. The energy production could be even higher in a different architectural concept, where the optimized sections would be used through all the length of the building. However, architectural reasons related to the perception of the built environment by the user, which consequently would affect also the behavior that it can generate, is going towards this architectural proposal.

Nowadays, the available tools, when they are used from the preliminary steps of the design, they can provide design and technical solutions for architectural expression, energy efficiency and needs as well as technological challenges.

The main purpose of this study was to define how on-site renewable energy production can be implemented in the design of a housing development from the first design phases, as well as to which extent can these strategies impact to the energy and CO2 balance.

It was demonstrated that through an optimization process, the final design of the buildings, following the architectural concept process, were able to increase energy production comparing to a conventional house by integrating photovoltaic panels on the roof. Furthermore, this design solution allowed preserving the Norwegian archetypic dwelling icon.

In conclusion, the integration of overall energy strategies can effectively reduce the ecological footprint of a housing development. Nevertheless to be able to recommend the implementation of those strategies, further research and follow-up should be done to acquire more quantitative data. In this sense, this work is a part of a wider work that aims to develop solar urban design recommendations for Øvre Rovoll neighborhood that will be presented in future works.

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